QUICK LAB

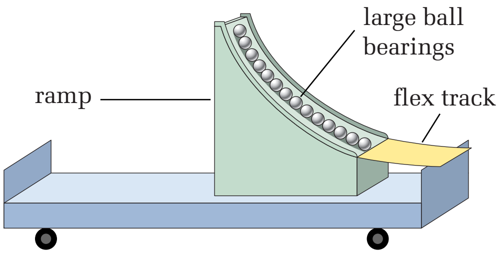
The Reaction Engine

TARGET SKILLS
- Hypothesizing
- Performing and recording
- Analyzing and interpreting

The Reaction Engine

According to Newton's first law of motion, an object requires a net force to push out in order to produce a change in speed or direction. If a rocket is out in space, what is available to provide this push? This activity should give you some ideas.

Set up a light dynamics cart with a ramp which could be made from Hot Wheels™ track as shown in the diagram. The ramp should be as high as possible and curved at the base so that ball bearings will be ejected horizontally from the back of the cart.



Arrange a track for the cart by clamping or taping metre sticks to the demonstration desk or tape them to the floor.

Place as many large ball bearings as possible on the ramp and hold them in place. Release the ball bearings and observe the motion of the ball bearings and the cart.

Analyze and Conclude

1. Describe the motion of the cart and the ball bearings. Did the last ball bearings move as quickly along the desk or floor as the first ones did? Did any actually end up moving in the direction of the cart?
2. Using Newton's laws of motion, explain why the cart accelerated.
3. What was the source of the energy that was transformed into the kinetic energy of the cart and the ball bearings?
4. The ramp with the ball bearings and a rocket are examples of reaction engines. Explain why the term is appropriate. What is the reaction mass in each case?

Apply and Extend

5. Research the topic of magnetohydrodynamic propulsion and prepare a brief report in diagram form. Where is this process mainly used?

Propulsion in Space

Newton's third law of motion states that if you exert a backward force on an object, that object will exert a forward force on you. In Chapter 4, Momentum and Impulse, you learned how Newton's third law led to the law of conservation of momentum. This concept is the basis for all motion and manoeuvring of astronauts and rockets in space. In fact, a spacecraft could be propelled by having an astronaut stand at the rear of the spacecraft and throw objects backward. This process is an example of recoil. As the astronaut pushed the objects backward, they would push just as hard forward on the astronaut.

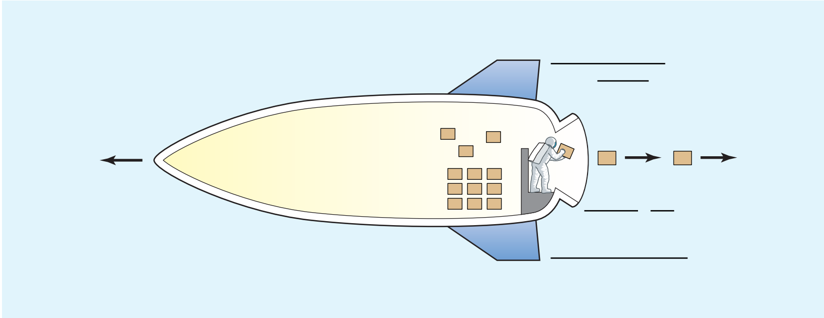


Figure 6.6 Recoil, a result of the conservation of momentum, is the basis of rocket propulsion. The concept is the same as the motion of an ice skater throwing a rock — a problem that you solved in Chapter 4.

Although this is the general principle on which rocket engines operate, most rely on hot, high-pressure gas to provide the reaction mass. The burning of the gas takes place in a **combustion chamber**, as shown in Figure 6.7. The walls of the combustion chamber exert a backward force on the gas, causing it to stream out backward. The gas in turn exerts a force on the walls of the combustion chamber, pushing it and the rocket forward.

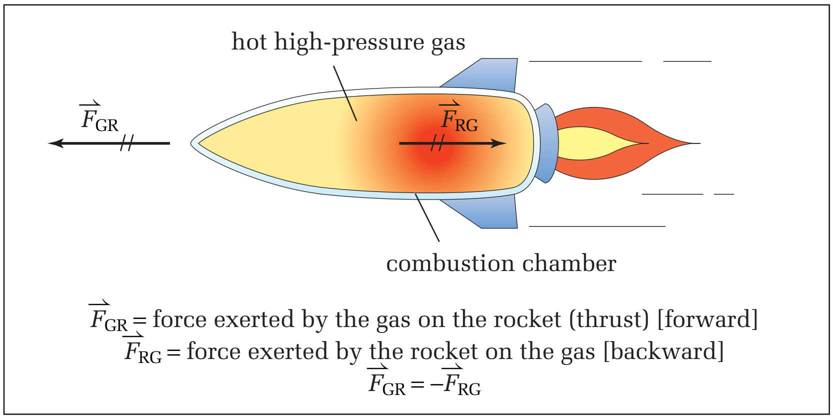


Figure 6.7 Newton's third law explains how the exhaust of gases creates thrust for a rocket.

The relationship between the motion of the gas and the forces on the gas can be found by applying the impulse momentum theorem: $\vec{F}\Delta t = m\Delta\vec{v}$. When physicists and engineers apply this theorem to rocket exhaust gases, they usually rearrange it as follows.

$$\vec{F}_{(\text{on gas})}\Delta t = m_{\text{gas}}\Delta\vec{v}_{\text{gas}}$$

$$\vec{F}_{(\text{on gas})} = \frac{m_{\text{gas}}\Delta\vec{v}_{\text{gas}}}{\Delta t}$$

$$\vec{F}_{(\text{on gas})} = \left(\frac{m_{\text{gas}}}{\Delta t}\right)\Delta\vec{v}_{\text{gas}}$$

In rocket technology, the term $\left(\frac{m_{\text{gas}}}{\Delta t}\right)$ is important because it represents the rate of flow of a given mass of exhaust in kilograms of gas per second. Because of the law of conservation of mass, it also represents the burn rate of the fuel and oxidizer combined. Since the gas is initially at rest in the combustion chamber, the $\Delta\vec{v}_{\text{gas}}$ represents the backward velocity of the gas relative to the combustion chamber of the rocket. This is also known as the

exhaust velocity. For most chemical propellants, the exhaust velocity ranges from 2 km/s to 5 km/s.

If you know the rate of combustion and the velocity of the exhaust gases, you can calculate the force with which the rocket pushes on the gas: $\vec{F}_{(\text{on gas})} = \left(\frac{m_{\text{gas}}}{\Delta t}\right)\Delta\vec{v}_{\text{gas}}$. According to Newton's third law of motion, this also represents the force with which the gas pushes on the rocket. This force is known as the **thrust** (action force, in Newton's third law). The gas experiences the reaction force and its mass is referred to as **reaction mass**.

The idea that the rocket exerts a force on the gas might seem strange, but when molecules of gas strike the walls, they exert a force on the walls. At the same time, the walls exert a backward force on the molecules of gas, causing them to recoil. The two forces are equal in magnitude, but opposite in direction.

PHYSICS FILE

As early as 1232 A.D., the Chinese were using gunpowder as a propulsive agent for arrows and incendiary bombs.

SAMPLE PROBLEM

Rocket Propulsion

A rocket engine consumes 50.0 kg of hydrogen and 400.0 kg of oxygen during a 5.00 s burn.

(a) If the exhaust speed of the gas is 3.54 km/s, determine the thrust of the engine

(b) If the rocket has a mass of 1.5×10^4 kg, calculate the acceleration of the rocket if no other forces are acting.

Conceptualize the Problem

- Because the hot gases *move* rapidly out of the combustion chamber, they have *momentum*.
- The *total momentum* of the gases plus rocket must be *conserved*; therefore, the *momentum of the rocket* must be *equal* in magnitude and *opposite* in direction to the gases.
- If you know the *change in momentum* of the rocket and the *time interval* over which that change occurs, you can determine the *force* on the rocket.
- From the *force* and the *mass* of the rocket, you can find its *acceleration*.

Identify the Goal

(a) The thrust, $\vec{F}_{\text{gas on rocket}}$, of the engine

(b) The acceleration, $\vec{a}_{\text{rocket}}$, of the rocket

Identify the Variables and Constants

Known	Unknown
$m_{\text{hydrogen}} = 50.0$ kg	$m_{\text{exhaust gas}}$
$m_{\text{oxygen}} = 400.0$ kg	$\vec{F}_{\text{gas on rocket}}$
$t = 5.00$ s	$\vec{a}_{\text{rocket}}$
$\vec{v}_{\text{exhaust}} = 3.54 \times 10^3 \, \frac{\text{m}}{\text{s}}$ [back]	
$m_{\text{rocket}} = 1.5 \times 10^4$ kg	

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Develop a Strategy

Find the total mass of the exhaust gases.

$$m_{\text{exhaust gas}} = m_{\text{hydrogen}} + m_{\text{oxygen}}$$
$$m_{\text{exhaust gas}} = 50.0 \text{ kg} + 400.0 \text{ kg}$$
$$m_{\text{exhaust gas}} = 450.0 \text{ kg}$$

Find the flow rate of the exhaust gas.

$$\text{Flow rate of the exhaust gas} = \frac{m_{\text{exhaust gas}}}{\Delta t}$$
$$\text{Flow rate of the exhaust gas} = \frac{450.0 \text{ kg}}{5.00 \text{ s}}$$
$$\text{Flow rate of the exhaust gas} = 90.0 \frac{\text{kg}}{\text{s}}$$

Use impulse equals change in momentum to determine the force on the gas.

$$\vec{F}\Delta t = m\Delta\vec{v}$$
$$\vec{F} = \frac{m\Delta\vec{v}}{\Delta t}$$

Since the gases started from rest relative to the combustion chamber, $\Delta\vec{v} = \vec{v}_{\text{exhaust}}$.

$$\vec{F} = \left(\frac{m}{\Delta t}\right)\Delta\vec{v}$$
$$\vec{F} = \left(90.0 \frac{\text{kg}}{\text{s}}\right)\left(3.54 \times 10^3 \frac{\text{m}}{\text{s}}\right)[\text{back}]$$
$$\vec{F} = 3.186 \times 10^5 \text{ N[back]}$$
$$\vec{F} \cong 3.19 \times 10^5 \text{ N[back]}$$

Use Newton's third law to determine the force on the rocket (combustion chamber).

$$\vec{F}_{(\text{gas on rocket})} = -\vec{F}_{(\text{rocket on gas})}$$
$$\vec{F}_{(\text{gas on rocket})} = -(3.186 \times 10^5 \text{ N[back]}$$
$$\vec{F}_{(\text{gas on rocket})} = 3.186 \times 10^5 \text{ N[forward]}$$

(a) The thrust on the rocket is 3.19×10^5 N[forward].

Use Newton's second law to calculate the acceleration of the rocket.

$$\vec{F} = m\vec{a}$$
$$\vec{a} = \frac{\vec{F}}{m}$$
$$\vec{a} = \frac{3.186 \times 10^5 \text{ N[forward]}}{1.5 \times 10^4 \text{ kg}}$$
$$\vec{a} = 21.24 \frac{\text{m}}{\text{s}^2}[\text{forward}]$$
$$\vec{a} \cong 21.2 \frac{\text{m}}{\text{s}^2}[\text{forward}]$$

(b) The acceleration of the rocket is $21.2 \frac{\text{m}}{\text{s}^2}$[forward].

Validate the Solution

The magnitude of the change in momentum for the rocket must equal the magnitude of the change in momentum for the gas, so

$$m_{\text{rocket}}\Delta v_{\text{rocket}} = m_{\text{gas}}\Delta v_{\text{gas}}$$
$$\Delta v_{\text{rocket}} = \frac{m_{\text{gas}}\Delta v_{\text{gas}}}{m_{\text{rocket}}}$$

The change in velocity is inversely proportional to the masses, so you would expect that the velocity of the rocket would be much less than the velocity of the gases. This is in agreement with the calculated value of the acceleration.

PRACTICE PROBLEMS

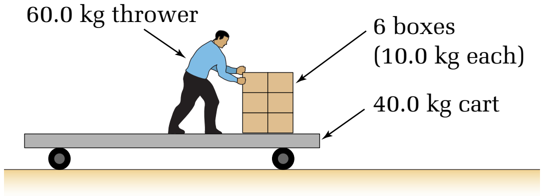
11. Determine the thrust produced if 1.50×10^3 kg of gas exit the combustion chamber each second, with a speed of 4.00×10^3 m/s.

12. What must be the burn rate in kilograms per second if gas with an exhaust speed of 4.15×10^3 m/s is to exert a thrust of 20.8 MN?

13. As an analogy for a reaction engine, imagine that a 60.0 kg person is standing on a 40.0 kg cart, as shown in the diagram. Also on the cart are six boxes, each with a mass of 10.0 kg. The cart is initially at rest. The person then throws the boxes backward, one at a time at 5.0 m/s *relative to the cart*.

(a) Determine the velocity of the cart after each throw, until you have the final velocity of the cart. Keep in mind that the mass on the cart decreases with each throw.

(b) Would the final velocity of the cart be different if the person had thrown all of the boxes at once with a velocity of 5.0 m/s[backward]? If there is a difference, give reasons for it.



The process of burning fuel to provide reaction mass is not the only way to generate a thrust. One extremely efficient method involves an ion engine, such as the one shown in Figure 6.8. In an engine such as this, gas atoms are ionized and the resulting positive ions are driven backward by electrostatic repulsion. The thrust is quite low, but it can act steadily month after month, gradually increasing the velocity of the spacecraft.

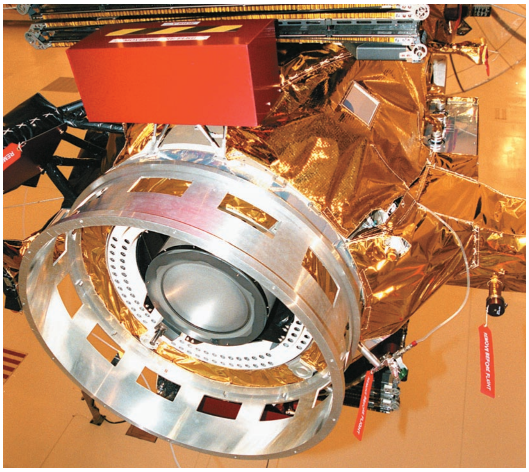


Figure 6.8 Experimental ion engine

TECHNOLOGY LINK

The *Deep Space 1* probe, launched on October 15, 1998, was the first spacecraft to use an ion engine. Xenon atoms are ionized and then repelled electrostatically, emerging from the spacecraft at speeds of up to 28 km/s and producing a maximum thrust of 90 mN. The spacecraft has enough propellant to operate continuously for 605 days.

Gravitational Assist

Sometimes, free energy seems to be gained for a spacecraft through a manoeuvre known as a **gravitational assist** or a **gravitational slingshot**. The process involves directing a spacecraft to swing around a planet, while keeping far from the atmosphere of the

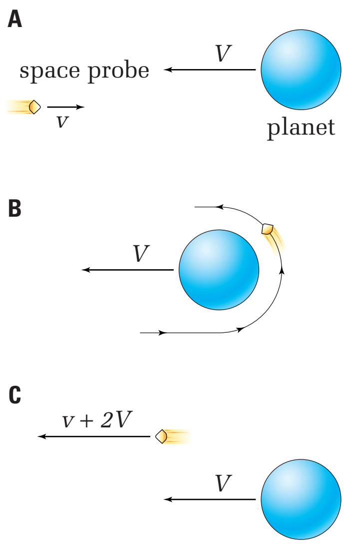


Figure 6.9 A celestial slingshot

planet. The interaction represents an extremely elastic collision, even through the objects do not actually meet. Figure 6.9 illustrates the process.

Earlier studies of elastic collisions showed that the speed of approach of colliding objects is equal to the speed with which they separate. In this case, the spacecraft is approaching the planet with a relative speed of $(v + V)$, where v is the speed of the spacecraft and V is the orbital speed of the planet. If the collision is elastic, the speed with which the spacecraft moves away from the planet must also be $(v + V)$. Since the planet itself is moving at speed V, the spacecraft must be moving at $V + (v + V)$ or $v + 2V$. As a result, if the spacecraft arcs around the planet and returns parallel to its initial path, it will gain a speed of $2V$, which is twice the orbital speed of the planet.

A similar effect can be seen on Earth. If a tiny Superball™ is held just above a more massive ball (such as a lacrosse ball) and they are dropped together, the Superball™ will rebound at high speed from the collision. The effect is shown in Figure 6.10.

In part (A) of the diagram, both balls are falling. Since they are close together, their speeds are about the same. In part (B), the large ball has hit the ground and is about to bounce upward. If that collision is elastic, it will rebound with the same speed it had just before hitting the ground, as shown in (C).

The two balls are now approaching each other, closing the gap between them at a speed of $2v$. If their collision is elastic, the speed with which they separate must also be $2v$. Because of the huge difference in their masses, the large ball is only slightly slowed down in the collision, and so is still effectively travelling at speed v. The small ball will therefore rebound with a speed that is $2v$ greater than the larger ball's speed. In other words, it will have a speed of $3v$.

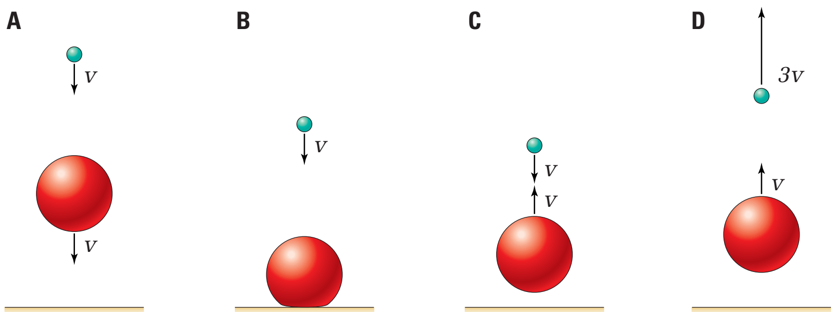


Figure 6.10 In elastic collisions, the speed of approach of colliding objects is equal to the speed with which they separate, as demonstrated by this experiment with a Superball™ and a lacrosse ball.

Because kinetic energy varies with the square of the speed, tripling the speed of the Superball™ will multiply its kinetic energy by a factor of nine. As a result, it will bounce to a height that is nine times its initial height.

This Superball™ discussion assumes that the collision is completely elastic. If there is some energy loss, the ball will not rise as high as predicted. The following investigation looks at just how elastic this collision actually is.